Discovery of the Millisecond X-Ray Pulsar HETE J1900.1-2455

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ABSTRACT

We report the discovery of millisecond pulsations from the low-mass X-ray binary HETE J1900.1-2455 which was discovered by the detection of a type I X-ray burst by the High Energy Transient Explorer 2 (HETE-2). The neutron star emits coherent pulsations at 377.3 Hz and is in an 83.3 minute circular orbit with a companion with a mass greater than 0.016 $M_\odot$ and likely less than 0.07 $M_\odot$. The companion star's Roche lobe could be filled by a brown dwarf with no need for heating or non-standard evolution. During one interval with an unusually high X-ray flux, the source produced quasiperiodic oscillations with a single peak at 883 Hz and on subsequent days, the pulsations were suppressed. We consider the distribution of spin versus orbital period in neutron star low-mass X-ray binaries.

Subject headings: pulsars: individual (HETE J1900.1-2455) — stars: neutron — X-rays: binaries

1. Introduction

Shortly after the discovery of radio millisecond pulsars, it was hypothesized that the neutron stars in low-mass X-ray binaries (LMXBs) were rotating at hundreds of revolutions per second and are the progenitors of radio millisecond pulsars (Alpar et al. 1982). The presence of rapidly rotating neutron stars in LMXBs was not conclusively established until the discovery of coherent millisecond pulsations from LMXBs (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). This discovery has greatly advanced our understanding of these systems. The unambiguous measurement of neutron star spin periods was essential in definitely establishing that the quasiperiodic oscillations found in thermonuclear X-ray bursts (Strohmayer et al. 1996) are linked to the neutron star spin. The highly accurate measurements enabled by the stability of the neutron star spin have enabled the most accurate measurements of the orbital properties of LMXBs. Spectral analysis of the pulse profiles has the potential to constrain the mass/radius relation of neutron stars and therefore the equation of state of nuclear matter (Poutanen & Gierliński 2003).

However, the sample of millisecond pulsars is small. Increasing the sample of millisecond X-ray pulsars is essential to enable population studies of these systems which should shed light on the properties of neutron-star X-ray binaries, their evolution, and their relation to millisecond radio pulsars. Here, we describe observations made with the Rossi X-Ray Timing Explorer (RXTE; Bradt, Rothschild, & Swank 1993) of a new transient X-ray source that we find to be a millisecond X-ray pulsar: HETE J1900.1-2455 (Vanderspek et al. 2005). We describe our observations in §2, our results on the detection of pulsations and the measurement of the orbital parameters in §3, and conclude in §4 with a few comments on the nature of the system and the population of neutron-star LMXBs.

2. Observations of HETE J1900.1-2455

On 2005 June 14, a bright X-ray burst was detected (Vanderspek et al. 2005) with the High Energy Transient Explorer 2 (HETE-2) (Ricker et al. 2003). The burst was clearly a type I X-ray burst

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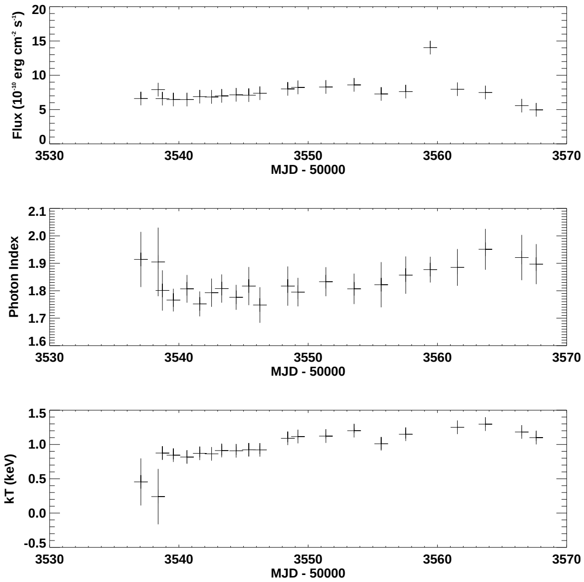

Fig. 1.— RXTE/PCA light curve of HETE J1900.1-2455. Each point is the flux in the 2-20 keV band derived from spectral fitting to an individual RXTE pointing.

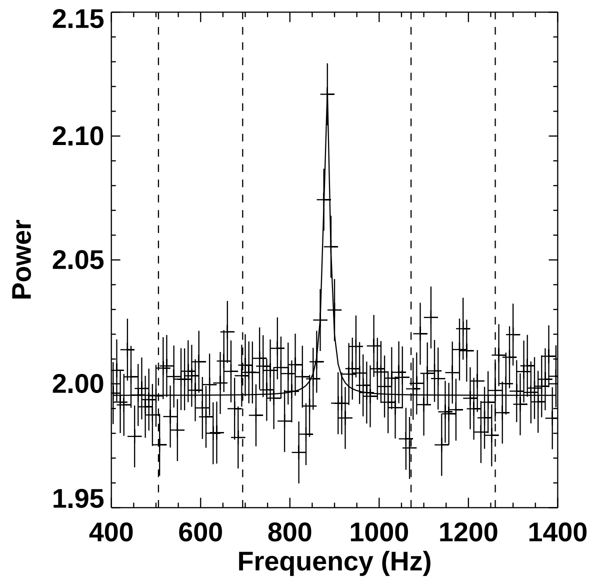

Fig. 2.— Leahy normalized power spectrum showing detection of a single kHz QPO. The solid curve represents the fit of a Lorenztian plus a constant to the data. The dashed lines indicate plus and minus the spin frequency and plus and minus half the spin frequency away from the kHz QPO centroid frequency.

with radius expansion. A detection in the HETE-2 Soft X-Ray Camera (SXC) (Villasenor et al. 2003) localized the burst to an $80''$ accuracy. No known X-ray burst source was consistent with the SXC position. Assuming that the burst luminosity is equal to the Eddington limit for a $1.4 M_{\odot}$ neutron-star burning helium, Kawai & Suzuki (2005) estimate the distance as 5 kpc.

Following discovery of the source, we triggered an RXTE Target-of-Opportunity observing program which led to multiple observations on dates from 2005 June 16 to July 16 (MJD 53537 to 53567). The first few RXTE pointed observations led to the detection of pulsations at 377.3 Hz (Morgan, Kaaret, & Vanderspek 2005) and further RXTE observations enabled an initial measurement of the orbital parameters (Kaaret, Morgan, & Vanderspek 2005). A position was determined from RXTE scanning observations (Markwardt et al. 2005) and then a possible optical counterpart was identified (Fox 2005). The optical counterpart was confirmed with further optical observations which showed that the source was bright compared with archival plates, blue in color, and emits a broad He II emission line (Steeghs et al. 2005). An improved X-ray position, accurate to $5''$, and consistent with that of the optical counterpart was obtained with the Swift X-Ray Telescope (Kong, Homan, & Lewin 2005). VLA observations were performed, but no radio counterpart was detected (Rupen, Mioduszewski, & Dhawan 2005).

For the RXTE observations, we analyzed data from the Proportional Counter Array (PCA). The first observation used two single bit modes, SB_125us_8_13_1s and SB_125us_14_35_1s, and an event mode, E_16us_16B_36_1s, to provide high resolution timing. The subsequent observations used a single event mode, E_125us_64M_0_1s, for high resolution timing. For all observations, the Standard-1 low-resolution (0.125 s) timing mode and the Standard-2 spectroscopic mode with 16 s time resolution were available.

A light curve derived from the PCA Standard-2 data is shown in Fig. 1. We used only data from PCU2 because this PCU was on during all of the observations and followed the analysis procedures described in Kaaret et al. (2002). A spectrum was extracted for each individual observation. We assign a 1% systematic uncertainty on

each spectral bin (Tomsick et al. 1999). We fit the spectra to a model consisting of the sum of a power-law and a black body with interstellar absorption. We fixed the absorption column density to $N_H = 1.5 \times 10^{21}\,\mathrm{cm}^{-2}$ which is the Galactic HI column density along the line of sight. The source has a Galactic latitude of $b = -12.87°$ and lies 1.1 kpc out of the plane if at a distance of 5 kpc. Therefore, the Galactic HI should mainly lie between us and the source.

The discovery X-ray burst occurred on 2005 June 14 (MJD 53535). The first RXTE pointing occurred 2 days later and shows the source at a flux of $6.6 \times 10^{-10}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The source flux increases gradually over the beginning of the outburst, there is one observation with a high flux at MJD 53559, and subsequently the source flux decays. The photon index gradually softens, while the blackbody temperature gradually increases, until a few days after the peak flux when the trends reverse. The first two observations may have had softer and cooler spectra, but the uncertainties in the spectral fitting do not permit any firm conclusions in this regard. We find temperatures higher than those reported by Campana et al. (2005). We do find that addition of a lower temperature blackbody improves the fit in some cases. The true spectrum of HETE J1900.1-2455 may include two blackbody components, as has been suggested for other millisecond pulsars (Gierliński & Poutanen 2005).

The spectral model described above was inadequate in fitting the high flux point because that spectrum shows distinct curvature at high energies. At energies below 14 keV, the spectrum lies above those from the previous or subsequent day, while at energies above 14 keV, the spectrum lies below. To fit that spectrum, we added a high energy exponential cutoff and removed the black body component. The resulting spectral model is the same as that commonly used for standard X-ray pulsars, i.e. those with spin periods of 1-1000 s (Pravdo et al. 1978; White, Swank, & Holt 1983). The photon index was 1.88 ± 0.05, the cutoff energy was $6.43 \pm 0.15\,\mathrm{keV}$, and the folding energy was $5.87 \pm 0.20\,\mathrm{keV}$. The cutoff energy is similar to that found for the X-ray pulsars GS 1843+00 (Piraino et al. 2000) and SMC X-1 (Naik & Paul 2004), but the photon index is softer than found for those or other standard accreting X-ray pulsars. We attempted to fit the spectrum with a blackbody, the sum of a blackbody plus a power-law, and the sum of two blackbodies and a power-law, all with absorption, but were unable to obtain good fits with any of these models. The RXTE/ASM light curve does not show unusually high flux near this time. The average rate around MJD 53559 is close to 3 c/s, equivalent to roughly $1.2 \times 10^{-9}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the 2-20 keV band. It appears unlikely that the high flux point is part of a superburst. We examined the light curve of this observation on time scales of 1, 8 and 64 s. The light curve shows no usual variability on these time scales, but does show a kiloHertz quasi-periodic oscillation (kHz QPO).

We searched for high frequency QPOs in each uninterrupted RXTE observation window and in combinations of the various data segments. We calculated averages of 16 s power spectra including events with energies below 18 keV from all PCUs. A single kHz QPO appears in the observation beginning MJD 53559.447583, see Fig. 2. The detection has a significance of 9.2σ, with no allowance for trials. Even allowing for 6×10^4 trials for all of the distinct frequency ranges in all the power spectra generated, the detection is still highly significant. The QPO has a centroid of $882.8 \pm 1.0\,\mathrm{Hz}$, a width of $16.9 \pm 2.4\,\mathrm{Hz}$, and an rms amplitude of 0.00787 ± 0.00086. There is no evidence for QPOs at plus or minus the spin frequency or at plus or minus half the spin frequency away from the single kHz QPO.

We used the Standard-1 data which has 0.125 s time resolution and no energy information to search for X-ray bursts. We found one burst-like event at MJD 53538.76433. However, this event appears to be a detector breakdown event and not an X-ray burst from the source. HETE-2 has reported only one additional X-ray burst on the HETE burst summary page[1] after the discovery burst. The additional burst was on MJD 53558, just before the point in the light curve with a high flux.

We examined the RXTE All-Sky Monitor (ASM) light curve for HETE J1900.1-2455. The only detection is of the current outburst. Therefore, the recurrence time of the transient is likely longer than 9 years.

[1] http://space.mit.edu/HETE/Bursts/summaries.html

Table 1

Parameters of HETE J1900.1-2455

Parameter	Value
Pulse frequency (Hz)	377.296171971(5)
Orbital period (s)	4995.258(5)
Projected semimajor axis (lt-ms)	18.41(1)
Epoch of 90° mean longitude (MJD TT)	53549.145385(7)
Orbital eccentricity	< 0.002
Pulsar mass function ($10^{-6} M_{\odot}$)	2.004(3)

Note.—These parameters assume the position reported by Fox (2005) of α = 19h 00m 08s.65 and δ = -24° 55′ 13″.7 (J2000). The trailing numbers in parenthesis indicates the $1-\sigma$ uncertainty in the final digits. TT indicates terrestrial time.

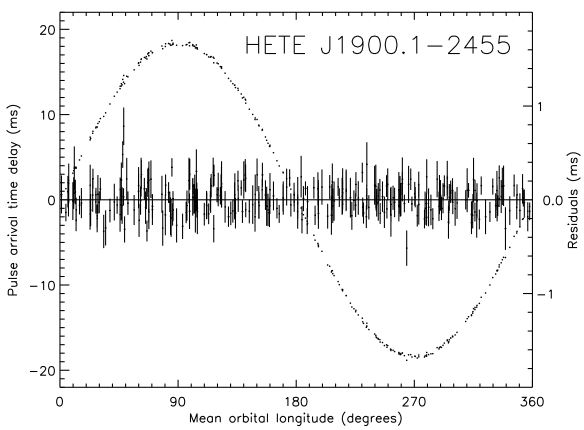

Fig. 3.— Pulse timing residuals for HETE J1900.1-2455. The points along the sinusoidal curve represent the timing residuals without the Keplerian orbit correction. The points centered about zero are the the timing residuals with the Keplerian orbit correction included and are multiplied by 10.

3. Pulsations

We searched for pulsations using the 125 μs time resolution data by correcting the event times to the solar system barycenter and then dividing the data into 256 s intervals, calculating a power spectrum for events in the 3–8 keV band (channels 8–32 in the 0-255 channel range) for each interval, and incoherently summing the power spectra for all intervals within a given pointing. A signal at 377.3 Hz was detected in the first pointed RXTE observation of HETE J1900.1-2455, but not at very high significance. However, signals near that frequency were detected in the following four RXTE pointings giving definite proof of the reality of the pulsations (Morgan, Kaaret, & Vanderspek 2005).

We searched the observations between June 17 and 22 for pulsations near 377.3 Hz. We divided the observations into 256 s intervals and found the pulse frequency in each interval. The pulse frequencies had a clear sinusoidal modulation, characteristic of modulation by orbital motion. We fitted a preliminary spin/orbit model to the frequency measurements to enable a pulse arrival time analysis as is standard in the timing analysis of pulsars (Manchester & Taylor 1977). In the preliminary model, we fixed the orbital eccentricity and pulse frequency derivative to zero. We corrected the photon arrival times using the preliminary spin/orbit model, and then calculated the epoch of the pulse peak within each interval. We then fitted the pulse arrival times using a linear least squares regression to find corrections to the spin and orbital parameters. The procedure was iterated as more observations became available and each set of new spin and orbital parameters were used to recalculate the pulse arrival times for the full data set.

The orbital and pulse timing parameters pre-

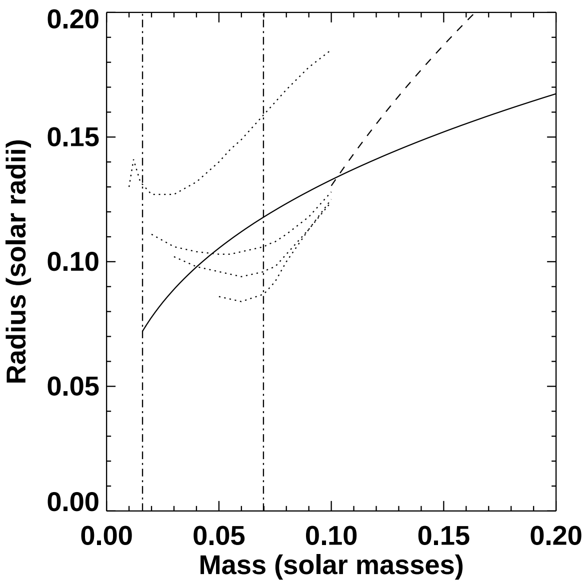

Fig. 4.— Mass-radius relation for the companion star in HETE J1900.1-2455. The solid curve indicates the mass-radius relation for the companion as required for a Roche-lobe filling companion with the measured orbital period. The dashed line represents zero-age main sequence stars with solar metallicity. The dotted curves represent brown dwarfs of ages 0.1 (top), 0.5, 1.0, and 5.0 (bottom) Gyr. The vertical dash-dot lines represent the lower mass limit and the 95% confidence upper mass limit.

sented in Table 1 were derived using the data from all observations before MJD 53558. Fig. 3 shows the residuals of the pulse arrival times with and without the correction for orbital motion. A good fit with $\chi^2/\mathrm{DoF} = 1.03$ is obtained without a spin frequency derivative or orbital eccentricity. The timing residuals are typically less than 500μs. The upper bound on the eccentricity is listed in the Table. We were unable to construct a phase-connected timing solution including data beyond MJD 53558. Observations on MJD 53559 showed the source flux to have brightened dramatically, see above, and the observed pulse frequency was shifted to 377.291596(16) Hz, $\Delta\nu/\nu \sim 6 \times 10^{-7}$. In subsequent observations, pulsations were suppressed. The rms pulse amplitude in observations before MJD 53558 ranged from 1.5% to 5%, while for observations after MJD 53559, we place an upper limit on the pulse amplitude of 1%.

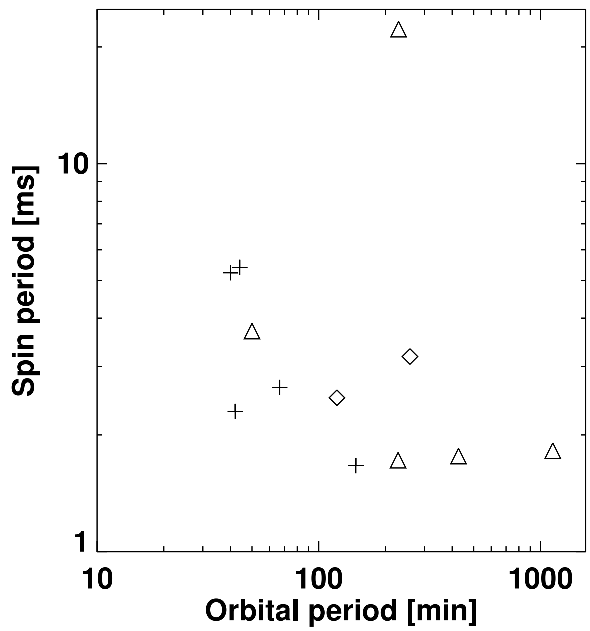

Fig. 5.— Spin versus orbital period for neutron star X-ray binaries with spin frequencies greater than 20 Hz – a 'milli-Corbet' diagram. Crosses are millisecond pulsars, triangles are burst oscillation sources, diamonds are sources with both.

4. Discussion

Our discovery of coherent millisecond pulsations from HETE J1900.1-2455 adds another to the six previously known X-ray millisecond pulsars (XMSPs). As now appears typical for XMSPs, the mass function for the pulsar is very small, $f_x = 2.0 \times 10^{-6} M_\odot$, implying either a very low mass companion or a very improbable orbital inclination. The minimum companion mass, assuming a neutron star mass of $M_X = 1.4 M_\odot$ and an orbital inclination $i = 90°$, is $m_2 > 0.016 M_\odot$. The 95% confidence upper limit on the mass, assuming a uniform a priori distribution in $\cos i$ and $M_X = 2.2 M_\odot$, is $m_2 < 0.07 M_\odot$.

If the companion star fills its Roche-lobe, then the density of the companion star is fixed by the orbital period (Frank, King, & Raine 1992). Fig. 4 shows the mass-radius relation for the companion star. Following Bildsten & Chakrabarty (2001), we have plotted the mass-radius relations for zero-age solar-metallicity main sequence stars (Tout et al. 1996) and for brown dwarfs of various ages from

Table 2
Neutron Star Spin Rates and Orbital Periods

Object	Spin Rate	Orbital Period	Type	Reference
	(Hz)	(min)		
EXO 0748-676	45	229	B	Villarreal & Strohmayer (2004)
XTE J1807-294	191	41.1	P	Markwardt, Smith, & Swank (2003)
				Markwardt, Juda, & Swank (2003)
XTE J1751-305	435	42.4	P	Markwardt et al. (2002)
XTE J0929-314	185	43.6	P	Galloway et al. (2002)
4U 1916-05	270	50.0	B	
HETE J1900.1-2455	377	83.3	P	This work
SAX J1808.4-3658	401	120.8	PB	Wijnands & van der Klis (1998)
				Chakrabarty & Morgan (1998)
IGR J00291+5934	599	147.4	P	Galloway et al. (2005)
4U 1636-536	581	228	B	
XTE J1814-338	314	256.5	PB	Markwardt, & Swank (2003)
X 1658-298	567	427	B	
Aql X-1	549	1137	B	

Note.—P indicates millisecond pulsars, B indicates burst oscillation sources.

0.1 to 5 Gyr (Chabrier et al. 2000). The points at which the stellar mass-radius relations intersect the mass-radius curve of the companion star indicate possible stellar companions allowed by the observations. In contrast to other XMSPs, there are possible Roche-lobe filling companion stars with standard evolutionary histories. Therefore, heating of the companion star, as suggested for SAX J1808.4-3658 (Bildsten & Chakrabarty 2001), is not required to expand the companion's radius and drive mass transfer in HETE J1900.1-2455. The companion star is likely a brown dwarf.

One very unusual aspect of our observations of HETE J1900.1-2455 is the detection of a dramatic brightening of the source on MJD 53559, accompanied by a shift in the pulse frequency with $\Delta\nu/\nu \sim 6 \times 10^{-7}$ and then the suppression of pulsations in subsequent observations. During the interval of high flux, the X-ray spectrum is exponentially cutoff at high energies, as is seen for standard X-ray pulsars, where the accretion spot is thought to be quite compact. What mechanism is responsible for the suppression of pulsations after the high X-ray flux interval is an open question. Diamagnetic screening of the magnetic field, a change in the accretion geometry, or enhanced scattering of the pulses due to accumulation of material around the poles are possibilities. Unfortunately, we do not have good information concerning the total fluence in the high flux event. However, the high flux point corresponds to a luminosity of only 1.5% of the Eddington luminosity, assuming that the Eddington luminosity is given by the bolometric flux of $9 \times 10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ reported for the discovery X-ray burst by Kawai & Suzuki (2005). Cumming, Zweibel, & Bildsten (2001) state that diamagnetic screening of the magnetic field is not possible for accretion rates below 2% of the Eddington rate, which may exclude this possibility.

In addition to the XMSPs, the spin periods of neutron stars in X-ray binaries can be measured via the detection of (quasiperiodic) oscillations in type I X-ray bursts. Table 2 presents the spin frequencies and orbital periods for neutron-star low-mass X-ray binaries with spin rates greater than 20 Hz and measured orbital periods. For the millisecond pulsars, the orbital periods are measured via pulse timing. For the X-ray bursters, the orbital periods are determined either via detection

of periodic dips in the X-ray emission or by optical observation of ellipsoidal modulation or Doppler-shifted absorption lines. X-ray dips are detected only when the inclination is high. The same information is presented in Fig. 5; a similar plot was presented by Swank & Marshall (2004). In deference to the name commonly used for plots of spin versus orbital period for standard X-ray pulsars (Corbet 1984, 1986), we refer to this plot as a 'milli-Corbet' diagram.

There are apparent bounds on the data points at low spin period and at low orbital period. The origin of the apparent lower bound on the orbital period, and the clustering of sources near this limit of 40 min, is a puzzle. There are LMXBs with shorter orbital periods, but the neutron star spin frequency has not been definitively measured in any of those systems. The lower bound on the spin period distribution has been interpreted as evidence that gravitational radiation losses limit the maximum accretion torque spinning up neutron stars in LMXBs (Chakrabarty et al. 2003). The longest spin period, for EXO 0748-676, is a factor of 4 larger than the second longest. The unusually slow spin may be due to an unusually high magnetic field (Villarreal & Strohmayer 2004).

If we consider the neutron stars with spin rates faster than 100 Hz, there appears to be a lack of points with long spin periods and long orbital periods. Excluding EXO 0748-676, the linear correlation coefficient between the logarithms of the spin and orbital periods is $r = -0.68$ which has a chance probability of occurrence of 2.5%. This correlation may indicate some coupling between the neutron spin and orbital period, perhaps indirectly if the mass accretion rate varies with orbital period. However, why EXO 0748-676 differs so significantly from the behavior of the more rapidly rotating neutron stars would need to be understood. The discovery of more millisecond pulsars, or the measurement of the orbital periods of additional X-ray burst oscillation sources, is needed to better understand the evolution of neutron star spin in low-mass X-ray binaries.

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